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DESIGN OF A LUNAR OXYGEN PRODUCTION PLANT

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Final Report  
NASA/ASEE Summer Faculty Fellowship Program - 1990

JOHNSON SPACE CENTER

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Date Submitted: August 17, 1990  
Contract Number: NGT-44-005-803

## ABSTRACT

To achieve permanent human presence and activity on the Moon, oxygen is required for both life support and propulsion. Lunar oxygen production using resources existing on the Moon will reduce or eliminate the need to transport liquid oxygen from earth. In addition, the co-products of oxygen production will provide metals, structural ceramics and other volatile compounds. This will enable development of even greater self-sufficiency as the lunar outpost evolves.

Ilmenite is the most abundant metal-oxide mineral in the lunar regolith. A process involving the reaction of ilmenite with hydrogen at 1000°C to produce water, followed by the electrolysis of this water to provide oxygen and recycle the hydrogen, has been explored.

The objective of this 1990 Summer Faculty Project was to design a lunar oxygen-production plant to provide 5 metric tons (mt) of liquid oxygen per year from lunar soil. The results of this study describe the size and mass of the equipment, the power needs, feedstock quantity and the engineering details of the plant.

## INTRODUCTION

The primary objective of this project was to design a plant to produce oxygen on the Moon from lunar materials. The Lunar Oxygen Production Plant is required to produce 5 metric tons (mt) of oxygen per year. The plant process selected for this study is the hydrogen reduction of ilmenite with soil feedstock. The plant consists of equipment for mining, processing, oxygen storage, and hydrogen storage. After construction or emplacement on the Moon, the plant will be teleoperated from Earth. The plant is assumed to have a duty cycle of 90% and a continuous power supply.

A simplified schematic of the hydrogen reduction of ilmenite process is shown in Figure 1. In this process, the bulk raw soil is mined and fed into the plant. The plant separates the very large and fine fractions of the soil so that an acceptable size of the soil can be processed. A system of storage hoppers then feeds the soil containing ilmenite into the top of a three-stage fluidized bed reactor. The reactor heats the soil to 1000°C as the soil flows down the reactor's three stages. Hydrogen gas flows up through the solids, mixes with the particles, and reacts with the ilmenite to form water vapor. An electrolysis cell separates the water vapor into hydrogen and oxygen. The oxygen is liquefied and stored. The hydrogen is fed back into the top section of the reactor. A solids settler removes the reactor residuals (spent solids) from the bottom of the reactor.

This report describes the different plant components. The results of the design are presented. The summary included shows the mass, power, and volume of the plant components.

### Assumptions

1. The required production capacity of the plant is 5 mt liquid Oxygen (LOX) per year using bulk lunar soil on the surface.
2. The concentration of ilmenite in lunar regolith can be as high as 10 volume percent (15 weight percent). However, a more likely value of 5 volume percent (7.5 weight percent) will be used in this design. An alternate design based on 10 volume percent of ilmenite (15% wt) concentration in regolith would be similar but the plant would be slightly smaller in size than the current design. Another advantage would be that the plant could produce more oxygen than the required 5 mt capacity if the feedstock contains higher percentage of ilmenite.
3. No beneficiation. This means there will be no enrichment steps included in the plant to increase the concentration of ilmenite in the soil.
4. Mining will be done only during the lunar day. At night, metals in the mining equipment could become brittle unless heated. The hot noon time also will be avoided. This requires the storage of sufficient mined regolith for operation during the night.
5. The plant operation is continuous with a 90 % duty cycle, allowing 10% of the time for trouble-shooting, maintenance and unexpected problems.
6. The process yield (chemical reaction and ilmenite conversion) factor is 0.9.
7. Lunar surface temperature varies from -100°C to +111°C. Assumed feedstock temperature is -20°C.

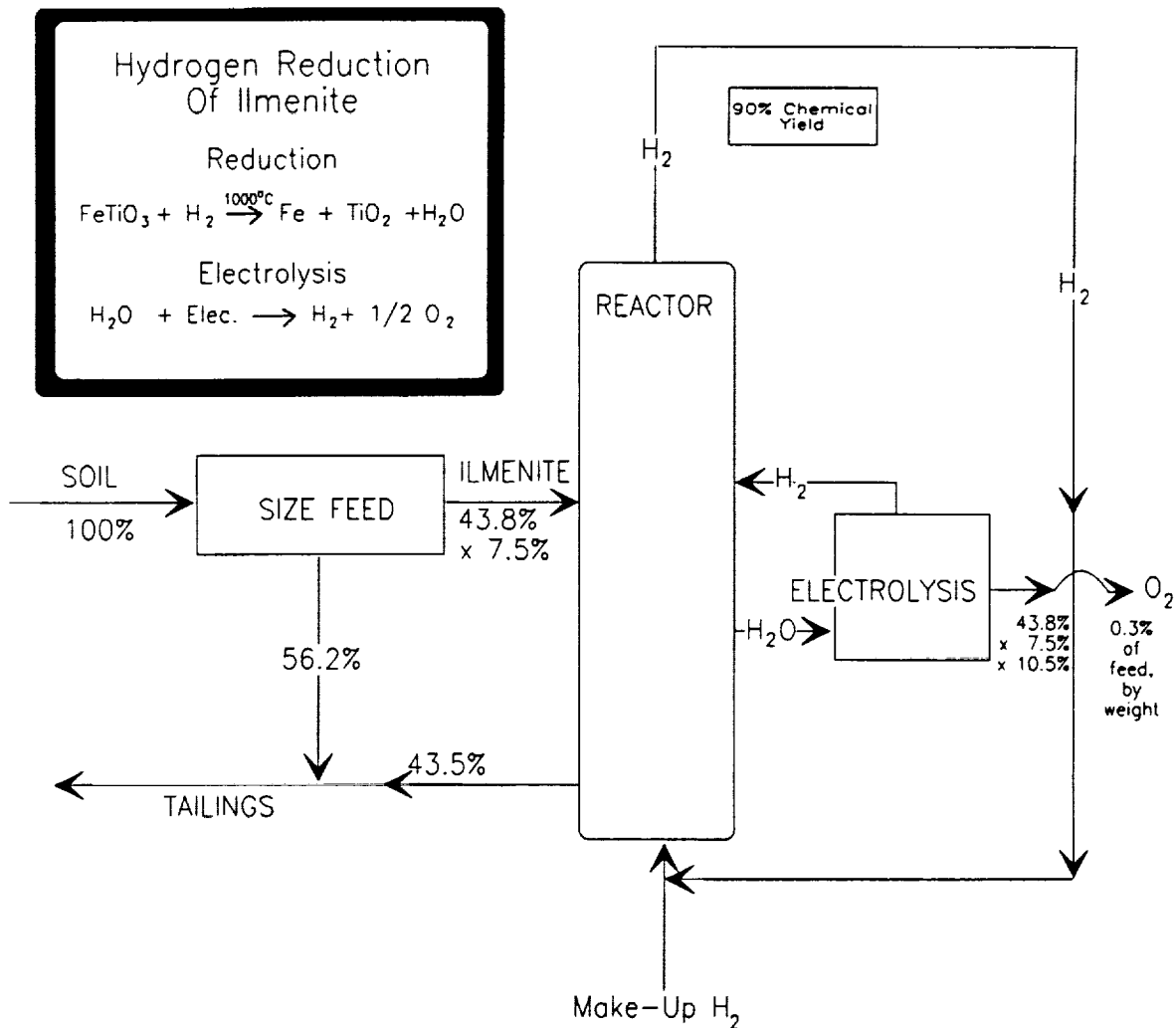


Figure 1  
 Simplified Schematic of  
 Hydrogen Reduction of Ilmenite Process

## LOX PRODUCTION PLANT

The oxygen production process is illustrated in Figure 2. Approximately 1620 metric tons of bulk soil feedstock is required per year. After removing the oversize and undersize rejects, a useful feed of 710 mt is available. As shown in Figure 1, considering a 7.5% wt of ilmenite concentration in the feed and a 90% yield of oxygen during the hydrogen reduction process, LOX production of 5 mt per year is obtained. The important components of the LOX production plant are described in the following sections.

### Mining

The mining equipment assumed is a front end loader and hauler. The front end loader (FEL) is a telerobotic vehicle for mining feedstock. The FEL can complete soil mining and will have sufficient time remaining to perform additional base operations.

One hauler is assumed. After being filled by the FEL, the hauler will travel to the process feed bin, dump the load, collect a load of tailings from the discharge bin, dump the tailings at the discharge area, and return to the mining site to start the new cycle over again.

The mining operation is on a 35% duty cycle, equivalent to 3066 hrs. The operation will be discontinued during lunar noon and night. The mining equipment has excess capacity. Since there will be a need for the installation of additional units to increase the oxygen production in the future, the excess capacity of the FEL and hauler is justified.

### Bulk Storage Feed Bin

Since the plant is run on a 90% duty cycle and the mining equipment is operated on a 35% duty cycle, the feed bin is sized to hold enough soil to run the plant during the lunar night (14 days). Using high-strength polyethylene fiber Spectra 1000<sup>(TM)</sup> in place of Al 2024 is recommended. The shell with 2 mm thick fiber Spectra 1000<sup>(TM)</sup>, and 1-cm-thick low-density insulation to provide protection from radiation and temperature effects reduces the mass of the bin considerably. Furthermore, this fabric might be compacted into a much smaller volume for transport to the Moon.

### Coarse Screen

The coarse Screen removes the oversize size unwanted rocks (material >0.5 mm) in the soil to discard bin (but see recommendations for an alternative).

### Fine Vibrating Screen

The minimum allowable feed size to the reactor is 0.45 mm. A vibratory screen was selected to remove fines.

### Feed Hoppers (2)

Two hoppers will be used to minimize gas losses from the reactor. The capacity of each hopper is adequate for 3 days of feedstock. Feedstock is fed into the reactor continuously from the bottom hopper which is maintained at 10 atm. pressure. When inventory in the bottom hopper is at an appropriate low point, the top hopper, which is

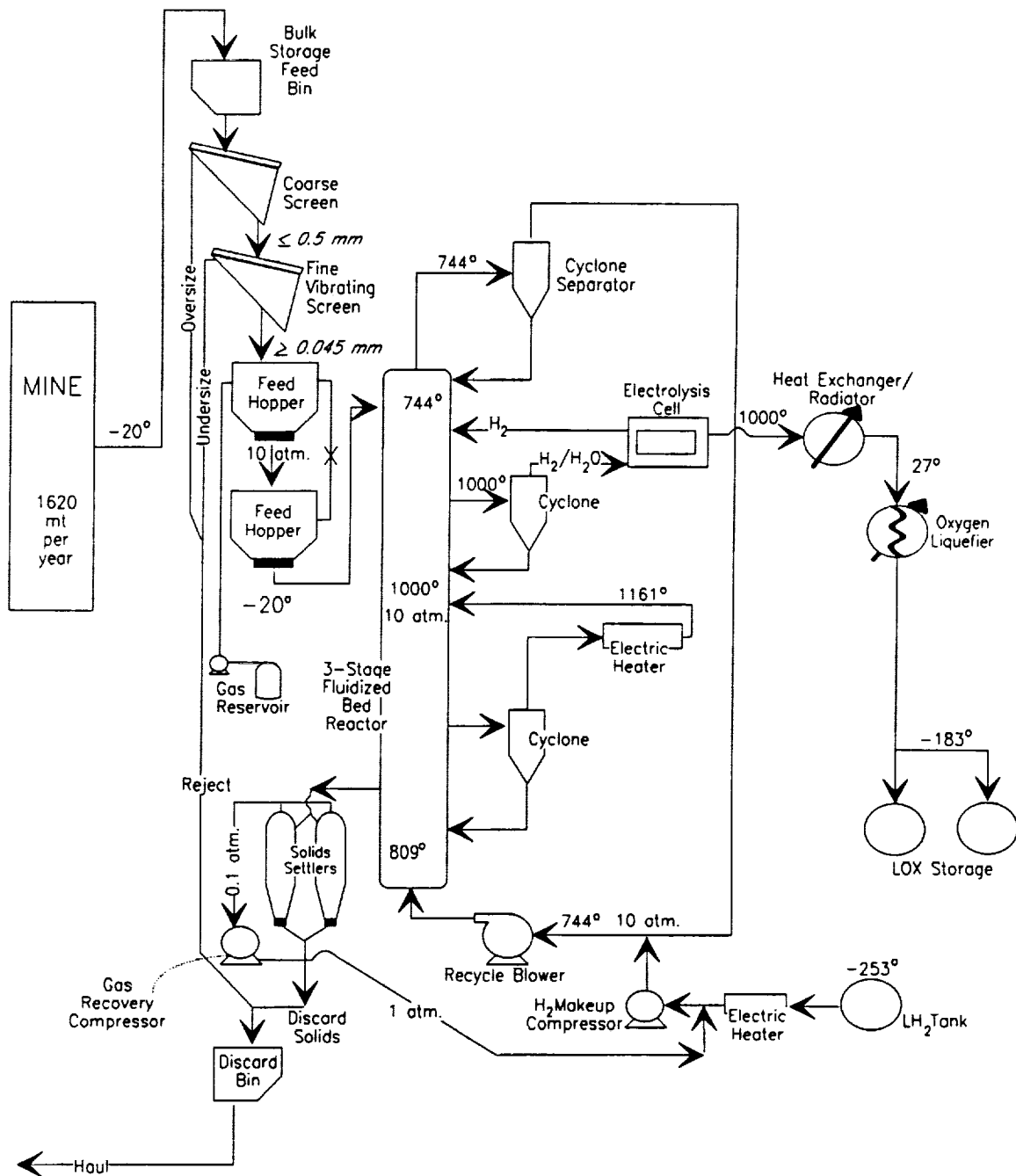


Figure 2  
Hydrogen Reduction of Ilmenite  
LOX Production Plant

operating normally in vacuum, is pressurized to 10 atm. Then a valve between the two hoppers is opened to rapidly re-inventory the bottom hopper. After the valve between the hoppers is closed, hydrogen gas in the top hopper is recovered. The design allows continuous feed to the reactor and minimizes gas losses from the reactor.

### **Reactor**

Ilmenite reduction takes place in a three-stage fluidized bed reactor (shown in greater detail in Figure 3) at 1000°C and 10 atm. pressure. The reactor in the LOX pilot plant (Ref. 1) was designed to use beneficiated feed rate of 71.29 kg/hr to produce 24 mt of oxygen per year. The reactor required in the current design will use unbeneficiated feed at a rate of 90 kg/hr to produce 5 mt of LOX per year. Since the feed quantity is nearly the same, the overall reactor dimensions of the pilot plant were maintained in the current design. However, several specific details have been modified as required to conform to the needs of the current design goals. The interior diameter of the reactor is 0.31 m at middle bed section. In consideration of the temperature variation existing in the middle (1000°C), bottom (809°C), and top (744°C) beds, the diameter of the reactor is designed to be 0.279 m and 0.267 m at the bottom and top beds, respectively, to maintain the gas velocity at 1 ft/sec in all the three beds. Reactor input material is restricted to sizes greater than 0.045 mm to avoid excessive carryover of fines to avoid clogging up of the system and less than 0.5 mm to allow fluidization to occur. Thus, the residence time of solids is 50 minutes in the top bed, 1.4 hours in the middle bed, and 50 minutes in the bottom bed. The total residence time of the solids in the reactor is 3.08 hrs. The central 0.31 m core of the reactor was surrounded by 7.5 cm of high-density (S.G. 2.24) super-duty firebrick to withstand the erosional nature of the high temperature gas/particles in the fluidized beds. Surrounding this is 23 cm of low-density (S.G. 0.14) insulation. The height of each bed in the reactor has been determined so that there will be enough space above the volume occupied by the solids for disengaging entrained solids. The outside diameter and height of the reactor are 0.9 m and 6.6 m respectively.

### **Electric Heater**

The electric heater heats the gas stream entering the reactor middle bed.

### **Electrolysis Cell**

The solid-state electrolysis cell, operating at 1000°C, separates the hydrogen and water vapor coming out of the reactor into hydrogen and oxygen. The hot hydrogen is recycled to the top bed of the reactor.

### **Recycle Blower**

The recycle blower circulates the hydrogen gas. Gas from the blower enters the reactor at the bottom bed plenum chamber.

### **Cyclone Separators**

The cyclone separators separate the solids from the gases. The cyclone separators contain no moving parts. Dust in the exit gas coming out of each of the reactor beds is removed to prevent the clogging of the system. This dust is returned to the reactor below the surface of each bed.

### **Solids Settlers**

Two solids settlers have been proposed to allow continuous flow of "spent" solids from the bottom bed. Each hopper is sized to allow 2 days residence time for the solids

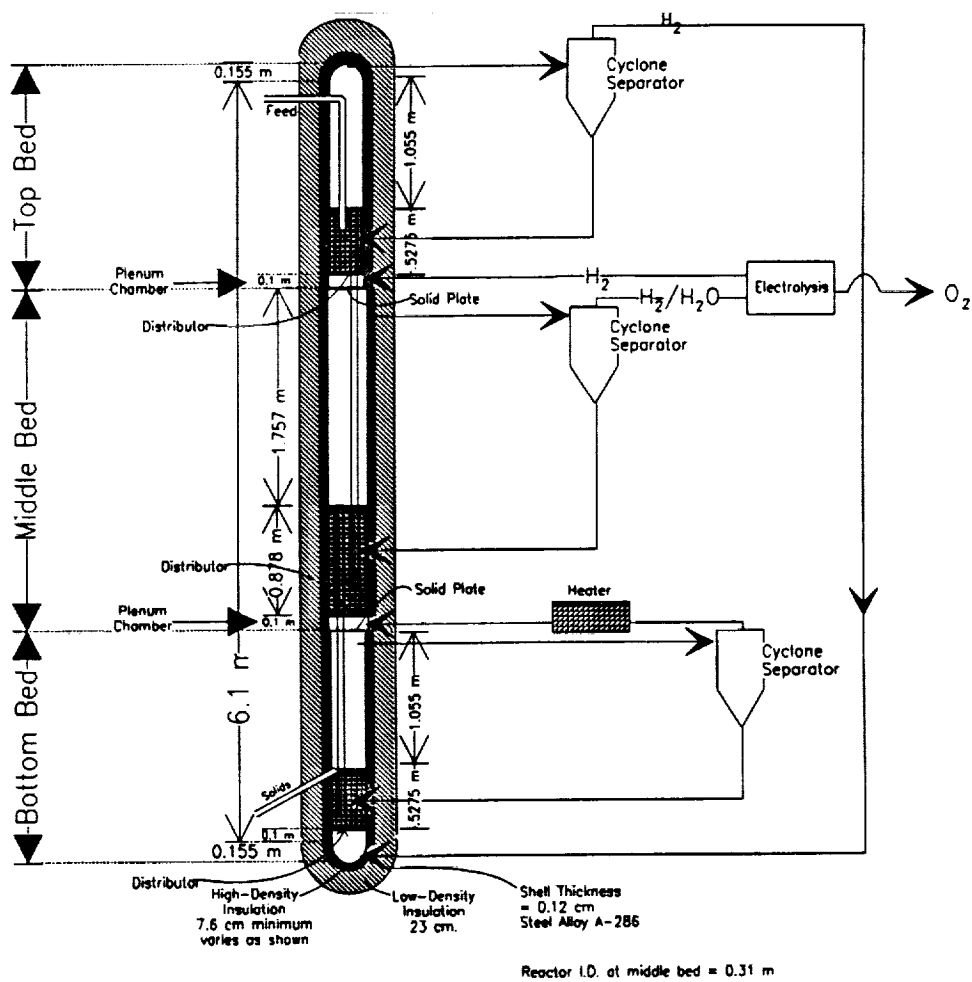


Figure 3  
Reactor Details



to settle and separate trapped gases. A gas loop recovers the hydrogen gas and recycles it through the H<sub>2</sub> make-up system. Solids will be allowed into one hopper while the other would be reduced to 0.1 atm. or less to recover gases. This arrangement may also facilitate the addition of a heat recovery system in the future. By putting compressors in series, as shown in Figure 2, the power of each is minimized and redundancy is provided.

#### **Radiator/Thermal Control System (TCS) (not shown)**

The radiator/thermal control system rejects the waste heat from oxygen liquefaction equipment. The TCS uses heat exchangers and an appropriate cooling medium. The radiator is positioned to keep the radiator permanently shaded from the sun.

#### **Oxygen Liquefaction and LOX Storage**

The oxygen produced by the electrolysis cell is liquefied by a stirling cycle refrigerator. The liquid oxygen is stored in two buried tanks. The re-use of tanks from an abandoned lunar excursion vehicle (LEV) is recommended. This will reduce mass and is a good substitute for new LOX storage tanks brought from Earth.

#### **Hydrogen Make-up System**

The hydrogen make-up system includes a tank, a heater, and a compressor. The tank contains enough hydrogen for six months of process leaks and losses. Resupply will be necessary at that time.

#### **Discard Bin**

This bin holds 15 days quantity of spent solids for disposal.

#### **Support Structure (not shown)**

The process support structure is mounted in the vertical direction to allow gravity flow of the solids in the reactor.

## **RESULTS**

A list of mass, power and dimensions for the equipment required in a 5 mt per year LOX production plant is given in Table 1. The process plant mass, not including mining equipment (front-end loader and hauler) is 5600 kg. The electric power required is 49.0 kW. Plant equipment was sized using the equations, methods and scaling indicators described in Ref. 1.

## **SUMMARY AND CONCLUSIONS**

1. While there are several ways to produce oxygen from lunar materials, the process of reducing ilmenite with hydrogen was considered in this design.
2. Using bulk lunar soil as feedstock without beneficiation components reduces total equipment mass significantly. The mass of the beneficiation components for the 24 mt pilot plant was 3879 kg (Ref. 1). The current design, without beneficiation components, does not require a large-size reactor and the process plant is a viable option. This trade needs to be evaluated for larger production rates.
3. Delivery of small, modular oxygen-production units is easy compared to delivery of a large production plant. Several of the modular units can be deployed and

**TABLE 1.**  
**LUNAR OXYGEN PRODUCTION PLANT EQUIPMENT**

5 mt/yr, H<sub>2</sub> Reduction of Ilmenite  
Ilmenite in regolith = 7.5% wt. No beneficiation.

Equipment	Total Mass (kg)	Total Power (kW)	Dimensions			
			W/D (m)	L (m)	H (m)	V (m <sup>3</sup> )
<b><u>Mining</u></b>	<i>Rate 1620 mt/yr</i>					
Front-end Loader (1)	2000	0.5	2.1	3.3	2.3	16
Hauler (1)	1000	0.2	2.5	4.0	2.5	25
Mining Total	3000	0.6				
<b><u>Feed Preparation</u></b>	<i>Rate 206 kg/hr</i>					
Feed Bin	176	0	4.5	--	3.0	40
Coarse Screen	15	0.5	0.5	0.8	0.4	0.2
Fine Screen	190	6	2.5	3.0	0.5	3.8
<b><u>Process</u></b>	<i>Reactor Feed Rate 90 kg/hr</i>					
Pressure Hopper 1	140	--	1.5	--	2.0	3.5
Pressure Hopper 2	140	--	1.5	--	2.0	3.5
Reactor	1960	--	0.9	--	6.6	4.4
Electric Heater	140	25	0.9	1.1	--	0.7
Electrolysis Cell	23	4	0.4	0.4	0.7	0.11
Recycle Blower	29	0.3	0.2	0.2	0.3	0.01
Cyclone Separators (3)	3	--	0.1	--	0.4	0.01
Solids Settlers (2)	288	--	1.2	--	2.0	2.26
Discard Bin	320	--	3.0	--	3.0	21
Oxygen Liquefier	40	1	0.3	0.8	--	0.06
Oxygen Storage Tanks (2)	120	--	1.0	--	--	0.5
Radiator/TCS	400	--	3.0	6.5	0.01	0.2
<b><u>Hydrogen System</u></b>						
Liquid Hydrogen Tank	1	0.5	0.5	--	--	0.05
H <sub>2</sub> Heater	1	0.1	0.1	0.1		--
H <sub>2</sub> Blower	2	0.1	0.1	--	0.1	--
<b><u>Process Piping</u></b>						
In reactor, 4 cm pipe	210	--	--	50	--	--
Others, 0.25 cm pipe	100	--	--	80	--	--
Process Total	4298	37.5				
Margin 30%	1302	11.5				
(includes support structure)						
<b><u>PLANT TOTALS</u></b>	<b>5600</b>	<b>49.0</b>				

erected on the Moon to increase the total oxygen production in stages. This may not result in economies of scale, but there are benefits in commonality, operations and construction.

4. A single "point design" to produce 5 mt of LOX per year using unbeneficiated lunar soil shows feasibility and indicates that the reduction of total plant mass is not trivial comparing the 24 mt/yr pilot plant.

5. The 5 mt/yr plant was designed for the feed rate of 90 kg/hr with 7.5% wt ilmenite concentration. If the soil contains a higher percentage of ilmenite (as much as 15% wt.), the process plant will be able to operate without any problem producing more oxygen with the same rate of feed. However, modifications relating to quantity of soil mining, feed rate, heat and power would make the plant operation efficient and effective.

6. Payback of plant mass occurs in one year of operation.

### RECOMMENDATIONS

1. The proposed use of a vibrating screen to remove fines of sizes less than 45 microns results in relatively large screen areas, power and mass. An alternate design may use air classifiers which lift the fines and allow the collection of useful material as a "heavy stock". The air classifier with aspirator, cyclone separator, fan and motor may replace the vibrating fine screen. This system can be introduced between top and bottom reactor feed hoppers. A substantial reduction in mass is expected. A detailed pressure analysis and design to incorporate air classifier to the LOX plant is needed. This will also provide the flexibility to change the minimum size limit of the feedstock as required, without replacing any parts. This could be useful if problems occur during operation, or if off-nominal operation is required, as in during start-up and shut-down.

2. Hands-on research to determine the optimum reactor configuration for maximum ilmenite conversion, especially for soil with high ilmenite concentration, is recommended.

3. More detailed design of dust removal and hydrogen removal from the process stream (water and hydrogen) to the electrolysis cell is required to avoid clogging and to reduce the load.

4. At least 90% of the feed to the reactor is rejected as waste at 809°C. Using this waste product and providing only a little more heat, the material can be sintered or even melted and cast into bricks and other products. Radiation and micrometeoroid shield design for the lunar outpost will be economical using cast basalt since the density could be as high as 2900 kg/m<sup>3</sup>. Casting the co-products of a lunar oxygen plant to form useable materials would be advantageous and may allow their use as radiation protection. This must be explored. Alternately, recovery of this heat value could lower the power requirements of the plant.

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